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Applying the Cognitive Apprenticeship Theory to Examine Graduate and Postdoctoral Researchers' Mentoring Practices in Undergraduate Research Settings*

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Graduate and postdoctoral researchers regularly mentor undergraduate research (UR) students, yet the literature examining the mentoring practices of these researchers in UR settings is scarce. This study explored the mentoring practices of 17 experienced and highly valued graduate and postdoctoral researchers by conducting semi-structured interviews and analyzing the responses using cognitive apprenticeship (CA) theory. The mentoring practices used during different UR periods (i.e., teaching a literature review process, teaching technical content, training in lab skills or experimental techniques, assisting with data analysis, assisting in creating presentation slides or a poster, and assisting in writing a final report) were identified and classified according to CA principles. The study findings can assist graduate and postdoctoral researchers who are mentoring UR students and can contribute to the development of training programs on mentoring UR students.

Keywords: cognitive apprenticeship; mentoring; qualitative research; undergraduate research

1. Introduction

1.1 Undergraduate research

Undergraduate research (UR) provides opportunities for undergraduate students to participate in scientific investigations by spending one or more semesters in research labs participating in typical research activities: designing research studies, conducting experiments, and analyzing and presenting results. Undergraduate research opportunities are readily available to engineering and science undergraduate students in U.S. universities, and they provide numerous benefits for participating students. Benefits include improved ability to conduct authentic research [1], to communicate effectively [2], and to think critically and independently [2–4]. Furthermore, the experience allows students to understand what it means to be a researcher working on real problems [5].

1.2 Undergraduate research student mentors: Graduate and postdoctoral researchers

One-on-one mentoring by experienced research team members is a typical component of the UR experience [6]. Mentoring is an important component of the UR experience because a correlation exists between the quality of mentoring relationships and positive undergraduate research experiences [5, 7].

In UR settings, there are more one-on-one mentoring relationships between undergraduate students and graduate or postdoctoral researchers than between undergraduate students and faculty [8, 9]. Multiple reasons explain why graduate or postdoctoral researchers mentor UR students more often than faculty. First, UR students work in the same labs as graduate or postdoctoral researchers, and therefore UR students naturally have more frequent interactions with them than with faculty. Second, UR students find it easier to talk about ideas with and ask questions of graduate or postdoctoral researchers [10]. Third, faculty often ask graduate or postdoctoral researchers to supervise UR students either because UR students' research projects are usually closely aligned with graduates' or postdoctoral researchers' investigations or because of faculty's multiple responsibilities [9].

One area of concern in this mentoring arrangement is that the mentors rarely receive training in mentoring UR students [11] and do not know how to mentor them effectively [6]. Studies have found that limited mentoring experiences and know-how can create numerous challenges for both mentors and mentees [10, 12]. When mentoring UR students, graduate or postdoctoral researchers may replicate their faculty's mentoring practices. However, mentoring graduate and postdoctoral researchers is different from mentoring UR students because of their differing expectations, work ethic, and commitment. One way to assist graduate or postdoctoral researchers with mentoring UR students is to inform them of practices successfully implemented by their peers and valued by UR students. However, the literature has not adequately examined successful graduate or postdoctoral researchers' mentoring practices in UR settings.

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2. Literature review and research question

Even though mentoring relationships between undergraduates and graduate or postdoctoral researchers are commonplace in UR settings, little research has examined these researchers' mentoring practices during various UR periods (e.g., conducting a literature review, learning technical content, and performing experiments).

Studies have examined the types of mentoring guidance provided to UR students from the perspectives of UR students [7, 8, 13] and faculty [9] but not from the perspectives of graduate students or postdoctoral researchers. However, examining their mentoring practices is crucial because they have the most frequent interactions with UR students, and their roles during the UR periods are different from those of faculty mentors. According to Dolan and Johnson [10] and Feldman, Divoll, and Rogan-Klyve [14], faculty are likely to assist UR students with project goals and long-term visions for research projects, whereas mentoring by graduate and postdoctoral researchers focuses on the technical aspects of a project and day-to-day problems. Thus, because the roles of the two groups differ, it is important to examine the mentoring practices from the perspectives of graduate and postdoctoral researchers.

Some studies have examined the perspectives of graduate and postdoctoral researchers on aspects, other than mentoring practices, of mentoring UR students. For example, Dolan and Johnson [10, 12] and Dooley and colleagues [15] examined these mentors' experiences or motivations for mentoring UR students. Ahn and Cox [16] identified important mentoring knowledge, skills, and attributes (KSAs) for graduate and postdoctoral researchers and developed a self-assessment tool to measure mentors' attitudes about their mentoring KSAs. Although these studies highlighted gains, challenges, and motivations and assessed important mentoring KSAs for graduate and postdoctoral researchers, they did not examine mentors' actual mentoring practices during UR research periods.

Linn and her colleagues called for studies of these mentoring practices. They pointed out that "the field would benefit from research that identifies mentoring practices and incorporates them into professional development for mentors, including graduate and postdoctoral researchers" [6, p. 1261757–5]. Studies revealing the perspectives of experienced graduate and postdoctoral mentors who have won the respect of their mentees will provide unique insight into their successful practices. Such studies will be enhanced by analyzing identified practices in terms of a specific theoretical framework, to situate the research in a scholarly conversation and to provide a commonly understood terminology for the analysis categories [17, 18].

Therefore, given that features of mentor-mentee UR settings align with novices' learning in cognitive apprenticeship (CA) theory, the author has selected CA as the theoretical framework and has conducted one-on-one interviews to investigate the mentoring practices of highly valued graduate and postdoctoral researcher mentors. The research question for this study is:

- What cognitive apprenticeship principles do graduate and postdoctoral researchers apply when mentoring UR students across various research periods, and how do they apply them?

3. Theoretical framework: cognitive apprenticeship

This section describes the CA theoretical framework and its application to this study.

The CA theory attempts to explain the process by which learners obtain knowledge from more experienced individuals through cognitive and metacognitive skills and processes [19]. The theory assumes that novices cannot accomplish learning on their own (at least in the early stages) but rather need to work with experts who show them the subtle, tacit elements of expert practices [20]. The theory asserts that through experts' help, learners gain practical and cultural knowledge of a common practice [7], gain motivation for learning [21, 22], and eventually become able to deal with the ambiguity and uncertainty of difficult tasks [23].

The auhor chose to examine mentoring practices in the context of CA theory because mentor-mentee UR settings and the theory share some important facets. For example, in mentored UR settings, UR students (i.e., novices) learn to conduct research by working with mentors (i.e., experts) who demonstrate certain research skills and provide feedback. Undergraduate research students, while working with mentors, learn to perform tasks in accordance with community norms. Furthermore, students are actively engaged in tasks independently and collaboratively in an authentic research environment. The alignment of these features of mentor-mentee UR settings with novices' learning in CA theory led us to choose CA theory as our investigative framework.

Collins, Brown, and Holum [24] and Collins [25] devised CA instructional strategies consisting of four dimensions—Content, Method, Sequence, and Sociology—to help learners gain mastery of tacit knowledge and abilities. The Content dimension includes the types of knowledge given to a

Table 1. Definitions of Cognitive Apprenticeship Dimensions and Principles

1.	**Content:** Knowledge provided to a UR student to develop a specific research skill
1.1	**Domain knowledge**—Mentor *provides* conceptual, factual, and procedural knowledge typically found in textbooks and other instructional materials.
1.2	**Heuristic strategies**—Mentor *provides* "tricks of the trade" or "rules of thumb" usually obtained indirectly through repeated practices.
1.3	**Control strategies**—Mentor *provides* strategies to monitor, diagnose, and remedy problems/activities (also known as metacognition).
1.4	**Learning strategies**—Mentor *provides* strategies to learn domain, heuristic, or control knowledge.
2.	**Method:** Methods used to develop a UR student's research skills
2.1	**Modeling—**Mentor *performs/demonstrates* a task/skill as a UR student observes.
2.2	**Explanation**—Mentor *explains* the steps associated with a task/skill.
2.3	**Coaching/Scaffolding**—Mentor *monitors* a UR student as he/she performs a task/skill and *assists or supports* the student when necessary.
2.4	**Reflection/Articulation**—Mentor *encourages* a UR student to think about his/her actions and/or to state reasons for his/her decisions verbally or in writing.
2.5	**Exploration**—Mentor *encourages* a UR student to try out different strategies and hypotheses and to seek knowledge independently.
3.	**Sequence:** Ordering/arrangement of tasks or activities to develop a UR student's research skills
3.1	**Increasing complexity (depth)—**Mentor *arranges* tasks from simple to complex (with respect to skills or concepts needed).
3.2	**Increasing diversity (breadth)—**Mentor *arranges* tasks from one setting to another (i.e., *provides* an opportunity for a UR student to apply a developed skill in other contexts/examples).
3.3	**Global to local skills—**Mentor *devises* tasks such that a conceptual map (or mental model) of the overall tasks is known/shared prior to completing/targeting individual tasks.
4.	**Sociology:** Social characteristics of the UR setting
4.1	**Situated learning**—Mentor *teaches* skills/knowledge in authentic contexts that reflect the way the skill/knowledge will be used in the future.
4.2	**Community of practice**—Mentor *creates* a learning environment in which a UR student can "actively communicate about and engage in the skills involved in expertise" (Collins, Brown & Holum, 1991, p. 16).
4.3	**Intrinsic motivation**—Mentor creates an environment that promotes the student's motivation for learning.
4.4	**Cooperation**—Mentor collaborates with a UR student for cooperative learning.

Note. Table adapted from Collins, Brown, & Holum [24].

learner, the Method dimension includes approaches taken to promote the development of expertise, the Sequence dimension includes the ordering of learning activities, and the Sociology dimension includes fostering the creation of community and cooperative learning.

These four dimensions (and their subcategories, known as principles) undergird this study by serving as the basis for data collection and interpretation. Specifically, the four dimensions were used to generate the interview protocol (see Appendix A) and to make sense of the interview data (i.e., interview responses were analyzed in terms of CA principles). The author hypothesized that the four CA dimensions and their principles can uncover and categorize different mentoring practices across various research periods in UR settings. The full list of the adapted applied CA dimensions and principles in UR settings is shown in Table 1.

4. Method

4.1 Context

The population of interest for this study was engineering graduate student or postdoctoral researchers who mentored UR students in a summer UR program and who were recognized by their UR students as outstanding mentors.

The summer UR program under study is run annually by the College of Engineering at a large research-intensive Midwestern university. The program supports undergraduates' research experience by matching students with faculty members who have similar research interests, by financially supporting UR students over the course of the program, and by offering various seminars and workshops on conducting research. To be eligible for the program, undergraduates must have completed four semesters of their degree with a minimum cumulative GPA of 3.0 of 4.0. Once in the program, students conduct 40 hours of research per week for 11 weeks and complete various assignments (e.g., write an abstract, complete a final report, and present their research at the program symposium). Approximately 120 first-time UR students participate in the program every summer.

Before the start of the program, faculty members pair their UR students with a graduate student mentor or a postdoctoral researcher mentor. There is no financial support for these mentors;

however, at the conclusion of the program, a number of them are recognized through the Outstanding Mentoring Award given by the program. The nomination and selection processes for the award begins when the program manager sends a nomination form to all the UR students a few weeks prior the end of the program. Students who wish to nominate their mentor for the award can complete the form. The submitted nomination forms are reviewed by two or three graduate assistants to the program, the program manager, and a number of senior faculty members in the College of Engineering. The awards are given to four or five mentors every summer.

The mentors who were nominated by their UR students during the 2012 and 2013 program sessions formed the population of interest for this study. A total of 36 mentors were nominated during these sessions, and 17 of the 36 nominated mentors agreed to be interviewed. The criteria used to select the participants are appropriate because the mentors were experienced and were recognized by their mentees as outstanding mentors. Thus, this select group of mentors is ideally qualified to provide information about their key mentoring practices in UR settings.

4.2 Data collection

Data was collected through interviews because they can identify relatively uninvestigated behavior and interactions [26]. For the 17 mentors who responded to a recruitment email, interview times and locations convenient to the mentors were selected. One researcher conducted all 17 interviews in a closed room. Prior to each interview, the author described the purpose of the study and explained that an audio recording device would be used and that their responses would be held confidential. After the interviewees agreed to these terms, the researcher asked the interview protocol questions (Appendix A). On average, each interview took 45 minutes. Participant information is provided in Table 2.

4.3 Data analysis

Interview transcripts were coded using Atlas.ti 6.2 and Microsoft Word. The priori approach, outlined by Miles and Huberman [27], was followed to develop a CA framework codebook to guide examination of the CA principles that the mentors applied in the UR setting.

First, the four CA dimensions and their principles were defined after reviewing the literature on the CA framework and mentoring undergraduate students.

Second, the codes were created. The four CA dimensions formed the first-level codes, and the 16 principles belonging to the four CA dimensions formed the second-level codes, in keeping with the organization of dimensions and principles in the CA framework. For example, the first-level code "Content" had "Domain Knowledge," "Heuristic Strategies," "Control Strategies," and "Learning Strategies" as its second-level codes. These two levels of codes formed the primary "bins" for sorting the interview data.

Third, all 17 interview responses to the CA dimension questions were carefully read.

Next, four representative transcripts (in terms of participants' disciplines, gender, mentor status, and responses) were selected and the established codes were applied. The research team examined each unit of an idea presented in the transcripts and checked whether the existing codes did or did not encompass the response. Many questions were asked in this

Table 2. Demographic Composition of Interview Participants

Mentor Status	Discipline	Gender	Year Nominated	Domestic/ International
Postdoctoral researcher	Chemical engineering	Male	2013	Domestic
Doctoral student	Agricultural & Biological engineering	Male	2012 (A)	International
Doctoral student	Biological Science	Male	2012	Domestic
Doctoral student	Chemical engineering	Male	2012 (A)	Domestic
Doctoral student	Chemical engineering	Male	2013 (A)	International
Doctoral student	Civil engineering	Female	2012	Domestic
Doctoral student	Civil engineering	Male	2012	Domestic
Doctoral student	Industrial engineering	Male	2012 (A)	International
Doctoral student	Electrical & Computer engineering	Male	2013	International
Doctoral student	Electrical & Computer engineering	Male	2013	International
Doctoral student	Material Science engineering	Male	2013	Domestic
Doctoral student	Mechanical engineering	Male	2012 (A)	Domestic
Doctoral student	Mechanical engineering	Male	2012 & 2010 (A)	International
Doctoral student	Mechanical engineering	Male	2013 & 2012	International
Master's student	Agricultural & Biological engineering	Female	2013	Domestic
Master's student	Civil engineering	Male	2013	International
Master's student	Civil engineering	Male	2013	International

Note: (A) indicates a year in which a mentor received the mentoring award.

process, including "What is the interviewer saying?" and "Where does the data belong in the CA framework schema?" If needed, the team was prepared to create new first- or second-level codes if the data did not fit with any existing codes. However, all new codes developed in this process were third-level codes, that is, were codes that further categorized the second-level codes.

The completion of the above steps led to a draft version of the CA framework codebook that contained the dimension and principle definitions and examples of each principle taken from the four transcripts. The codebook was then used to code two different interview transcripts. Less than 10% of the total number of existing codes from the codebook were developed after reviewing these two additional transcripts. The coding of the six transcripts led to a solid final version of the CA framework codebook that had both conceptual order (i.e., the CA framework) and structural order (i.e., a hierarchical code system), which helped the author to (1) organize and retrieve codes when coding the transcripts and (2) place the data into their respective CA dimensions and principles. The codebook was used to code the rest of the transcripts.

5. Results

5.1 Mentors' goals during undergraduate research periods

Six distinct mentoring periods during the UR program were found after interviewing graduate and postdoctoral researcher mentors. Descriptions of UR student activities and mentors' goals for each period are presented below. Note that unless stated otherwise, from this point forward both graduate and postdoctoral researcher mentors will be simply referred to as mentors.

5.1.1 Period 1. Teaching a literature review process

In this period UR students were finding, reviewing, understanding, and summarizing past empirical research studies closely related to their research projects. Typically, students read studies written by their mentors or by other researchers in their research group. The mentors' goal was to familiarize students with the contents of existing studies, including experimental techniques used, experiments conducted, results found, conclusions made, and gaps filled and identified.

5.1.2 Period 2. Teaching technical content

In this period UR students learned governing equations and theories for their research (e.g., conservation of mass and momentum), how to simplify problems in their projects (e.g., simplifying multiple parameters to one or two parameters), and the background knowledge necessary to conduct their research projects (usually topics taught in undergraduate or graduate classes). The mentors' goal was to help students know or be able to locate relevant technical content.

5.1.3 Period 3. Training in lab skills or experimental techniques

In this period UR students learned to operate lab equipment (e.g., a high-speed camera) or to perform experimental techniques (e.g., extract a specific gas from a sample or measure crack growth). The mentors' goals were to help students to master equipment operation or required techniques and to understand the physics involved in these activities.

5.1.4 Period 4. Assisting with data analysis

In this period UR students applied equations or theories to transform experimental data (or raw data) into results that had meaning for the students' projects. This period also includes time that students spent interpreting their results and making sense of the trends in or shape of the results, which were usually in the form of graphs or tables. The mentors' goals were to help students recognize what was going on in their results and justify their conclusions with known theories or existing studies.

5.1.5 Period 5. Assisting with the creation of presentation slides or a poster

In this period UR students created presentation slides or a poster to use in presenting their research work to their peers, graduate students, postdoctoral researchers, and faculty, who may or may not be in the students' disciplines. The mentors' goal was to help students create effective slides and posters.

5.1.6 Period 6. Assisting with writing a final report

In this final period UR students documented their research, detailing every aspect of the work that they completed over the course of the UR program. The types of documents included summary reports for research group members and conference or journal papers targeted to an audience in the students' fields. The goal for the mentor was to help students to document their research study clearly and accurately for a specific audience.

5.2 Cognitive Apprenticeship principles applied by mentors during undergraduate research periods

The following section describes how the mentors used CA principles during each period.

5.2.1 Period 1: Teaching a literature review process

Of the 17 interviewed mentors, nine helped students with the literature review process. To teach students how to perform a literature review, the mentors provided both procedural knowledge (Domain Knowledge) and tricks of the trade (Heuristic Strategies). Some mentors demonstrated the literature review process (Modeling), while others provided guidance or gave suggestions (Coaching/Scaffolding) as their students independently performed the process. One mentor used the research group's papers to teach his student how to review and summarize scientific papers (Situated Learning) prior to having the student find, review, and summarize new papers (Increasing Diversity). Table 3 describes CA principles that mentors applied when teaching the literature review process.

5.2.2 Period 2: Teaching technical content

Of the 17 interviewed mentors, 12 discussed helping their students understand and learn the technical content that they needed to begin their project. The majority of the mentors provided references (Domain Knowledge) for their students. These references included review articles, course materials (e.g., class slides and notes), reference books, theses, and the mentor's preliminary exam document.

The mentors also met one-on-one with their students to discuss the texts and answer any questions the students might have about them (Coaching/Scaffolding). One mentor, however, encouraged his student to answer his own questions by further reviewing the materials provided (Exploration). Another mentor asked his colleague to teach the mentor's student the needed technical content (Community of Practice). The mentor leaned on his colleague to teach his student because the mentor believed the colleague was more knowledgeable in the area. Descriptions of the principles that mentors applied when teaching technical content are presented in Table 4.

5.2.3 Period 3: Training in lab skills or experimental techniques

During the UR program, all interviewed mentors ($N = 17$) taught lab skills or experimental techniques to their students, such as operation of a high-speed camera or extraction of gas composites. Many mentors mentioned the importance of training students in lab skills and experimental techniques to prepare them to conduct independent research.

The mentors performed this training in a lab (Situated Learning), and students participated in the mentors' own research project or other existing projects that required use of techniques that they needed to learn (Increasing Diversity). This hands-on approach helped students develop the targeted skills and techniques. The mentors' support included providing various types of references (e.g., textbooks, articles, manuals, websites, and course notes) (Domain Knowledge), sharing knowledge gained from past experiences (Heuristic Strategies), and indicating potential problems. They also advised on how to troubleshoot problems (Control Strategies). The mentors employed a sequence of steps: They first demonstrated and

Table 3. Cognitive Apprenticeship Principles Applied While Teaching a Literature Review Process

CA Principle	No. of Mentors	Principle Definition(s) in a UR Setting
Domain Knowledge	4	Mentors provided information on how to perform a literature review in a one-on-one meeting or group seminar. Shared information included where to search for scientific papers, how to determine whether a paper is relevant or irrelevant to a project, how to summarize a paper, and how to sort and organize papers for future referral.
Heuristic Strategies	4	Mentors provided the strategies they often used to find, search, understand, sort, and summarize the most cited papers.
Modeling	2	Mentors demonstrated the literature review process.
Coaching/Scaffolding	9	Mentors provided review papers or their research group's papers to familiarize students with the existing literature and to help them begin searching for additional papers. If applicable, mentors recommended searching for papers published within a certain time period (e.g., studies done in the last five years). Mentors suggested keywords and researchers' names that students could search for in a database or library. Mentors trained students on what to particularly notice when reading papers (e.g., specific sections in the papers).
Increasing Diversity	1	Mentor first asked his student to review and summarize the papers written by research group members and then helped the student to transfer those review and summary skills to new sets of papers that the student found.
Situated Learning	1	Mentor taught the skills needed to review and summarize papers using papers written by research group members.

Note: The "No. of Mentors" column represents the unique number of the interviewed mentors who applied each principle.

Table 4. Cognitive Apprenticeship Principles Applied While Teaching Technical Contents

CA Principle	No. of Mentors	Principle Definition(s) in a UR Setting
Domain Knowledge	11	Mentors provided references (e.g., review articles, journal papers, mentor's preliminary exam documents, class slides, theses, catalogs, textbooks, software manual) that students could study to become familiar with the technical content needed for their research.
Coaching/Scaffolding	6	Mentors discussed the reference materials with students. In the discussions, mentors answered students' questions and/or provided additional information that supplemented the materials to help students understand the basic knowledge (or technical content) that they needed to begin their research project.
Exploration	1	Mentor encouraged the student to use the references to find answers to their own questions, so that they could get a "sense of accomplishment."
Community of Practice	1	Mentor had a colleague (e.g., other graduate student in the lab) teach technical content to their student.

Note: The "No. of Mentors" column represents the unique number of the interviewed mentors who applied each principle.

Table 5. Cognitive Apprenticeship Principles Applied While Training in Lab Skills or Experimental Techniques

CA Principle	No. of Mentors	Principle Definition(s) in a UR Setting
Domain Knowledge	10	Mentors provided references (e.g., websites, tutorials, articles, textbooks, in-housed procedure, manuals, and class slides) that students could read to learn skills/techniques.
Heuristic Strategies	6	Mentors shared knowledge they had gained from past experiences, including the advantages and disadvantages of (or subtle differences between) differing processes that achieve the same outcome, common novice mistakes, how to estimate how long each step should take, and information about the critical steps in a process.
Control Strategies	1	Mentor told the student what to do when there was a problem. Specifically, the mentor informed the student about potential problems that could occur and how to troubleshoot them.
Modeling	11	Mentors demonstrated a skill/technique multiple times (e.g., operating a machine or a tool) as students watched and learned.
Explanation	10	As mentors demonstrated a skill/technique, they explained what they were doing, how they were doing it, and why they were doing it. Some mentors used equations and diagrams in their explanations.
Coaching / Scaffolding	14	Until students were comfortable performing a skill/technique on their own, mentors were present while they performed it. While present, mentors answered students' questions as they completed each step in a process, demonstrated and explained procedures multiple times, pointed out mistakes students made and corrected them, gave students supplementary tasks to complete, gave recommendations/tips on how to complete a procedure accurately and efficiently, and helped troubleshoot problems.
Reflection / Articulation	2	Mentors asked questions designed to check students' understanding or to have students reflect on what they had done. Mentors also asked students to explain what they were doing as they completed each step in a process.
Exploration	4	Mentors gave students opportunities to independently explore different approaches to performing a skill/technique, as long as safety and cost were not issues.
Increasing Diversity (breadth)	9	Mentors first had students develop skills/techniques while working on mentors' (or existing) experiments and then had students transfer/apply the learned skills to their own research work.
Situated Learning	9	Mentors taught new skills/techniques in an authentic environment (e.g., in the lab, with real data, or during an experiment).
Community of Practice	9	Mentors reached out to collaborators (or other lab members) who were more experienced with a specific skill/technique and had them teach or train students. After training students, mentors provided opportunities for them to perform the skill/technique without supervision. During these times, mentors remained available to help or to answer questions.
Cooperation	5	Mentors and students worked and learned new skills or techniques together. This occurred when mentors were not familiar with the skills/techniques that students needed to know.

Note: The "No. of Mentors" column represents the unique number of the interviewed mentors who applied each principle.

described a technique (Modeling, Explanation), then they allowed their students to perform the technique while they observed, and finally they coached and provided scaffolding remarks that helped the students master the technique (Coaching/Scaffolding). Once their students were confident, the mentors allowed them to perform the technique without supervision. However, the mentors made themselves available via telephone or made sure to be in a nearby location in case students needed to reach them (Community of Practice). Table 5 provides further details about the principles that the mentors applied and how they applied them in this period.

5.2.4 *Period 4: Assisting with data analysis*

All but one mentor discussed assisting their students with analyzing and interpreting the students' experimental data. Similar to what was highlighted in other periods, the mentors provided a set of references to help their students analyze and interpret data. The Learning Strategies principle was also observed in this period, when one mentor challenged his student to develop a program code that took the experimental data as the code's input and output analyzed results. This mentor believed that the process of developing a code to interpret results had been beneficial for his student because it taught the student about governing equations and theories and demonstrated how they applied in the analysis.

The Coaching/Scaffolding principle encompassed a variety of scaffolds that the mentors used to help their students analyze data, such as visual scaffolds, prompts, suggestions, explanations, and discussions. The Reflection/Articulation principle is evident in instances when the mentors encouraged their students to summarize (or describe) what they observed in the results and to synthesize the existing literature or theory. The mentors assisted their students to summarize and synthesize results by asking questions that stimulated the students to reflect on their conclusions or make connections with what they had learned from classes or previous reading.

This was the only period during which the Global to Local Skills principle was observed. The principle was revealed when the mentors had their students predict what they would expect to see from the data prior to any analysis. Some mentors encouraged their students to ponder whether the trends in their data or the shapes of their graphs were consistent with the students' expectations. Finally, the Cooperation principle was seen when mentors and students worked together to analyze data. The principles applied in the data analysis period of the UR program are shown in Table 6.

5.2.5 *Period 5: Assisting with the creation of presentation slides or a poster*

As the students prepared their posters or presentation slides for the UR symposium, the mentors applied the Domain Knowledge, Heuristic Strategies, Coaching/Scaffolding, Reflection/Articula-

Table 6. Cognitive Apprenticeship Principles Applied While Assisting with Data Analysis

CA Principle	No. of Mentors	Principle Definition(s) in a UR Setting
Domain Knowledge	4	Mentors provided references (e.g., scientific literature and textbooks) that students could use to help them interpret the data from their research project.
Learning Strategies	1	Mentor had the student develop a tool to use for data analysis. The mentor believed that the process of developing this tool would familiarize the student with the governing equations and theories that the student needed to know to interpret their results.
Coaching/Scaffolding	12	Mentors used various types of scaffolds to help students interpret data, including visual scaffolds, prompts (e.g., asking questions that guided students to think through difficult/new concepts), suggestions, guidance (e.g., encouraging students to plot data first before analyzing it with statistics), and explanations. Mentors also taught students how to manage their time during the interpretation stage of a research project so that enough time is left to interpret data before the project ends, reviewed and discussed the viability of students' interpretations, helped students to synthesize their results with existing literature (or governing equations), and helped students learn the background knowledge necessary for interpreting their data.
Reflection/Articulation	5	Mentors had students summarize or describe in detail what they saw (or what they believed was happening) in their results and questioned/challenged students' summaries or interpretations.
Global to Local Skills	4	Mentors discussed expected results prior to having students analyze their data. Some mentors had students hypothesize what they might see, before performing any analysis.
Cooperation	6	Mentors and students worked together to analyze and interpret data.

Note: The "No. of Mentors" column represents the unique number of the interviewed mentors who applied each principle.

Table 7. Cognitive Apprenticeship Principles Applied While Assisting with the Creation of Slides (S) or a Poster (P)

CA Principle	No. of Mentors	Principle Definition(s) in a UR Setting
Domain Knowledge	1 (P)	Mentor shared articles on making a good scientific poster.
Heuristic Strategies	1 (P)	Mentor gave advice or tips on making a good poster based on the mentor's past experience.
Exploration	5 (S) 7 (P)	After initial guidance (i.e., showing existing posters, discussing what to include and exclude, and suggesting an outline), mentors had students design the presentation slides or poster.
Coaching/Scaffolding	7 (S) 8 (P)	Mentors helped students by reviewing the technical and non-technical content presented in their slides or poster (non-technical content included such matters as grammatical errors, formatting issues, appropriate use of words, and balance between pictures and words) and providing suggestions to improve the slides or poster. Mentors reviewed students' slides or poster multiple times as the students changed their work based on comments from their mentors. Mentors' remarks included things that were done well, that needed to be elaborated, or that needed to be removed.
Reflection/Articulation	1 (P)	Mentor asked the student to review the student's poster from the perspective of the reader.

Note: The "No. of Mentors" column represents the unique number of the interviewed mentors who applied each principle.

Table 8. Cognitive Apprenticeship Principles Applied While Assisting with Writing a Final Report

CA Principle	No. of Mentors	Principle Definition(s) in a UR Setting
Domain Knowledge	1	Mentor provided references that would help the student write a final report.
Coaching/Scaffolding	11	Support from the mentors included reviewing the technical aspects of students' reports (e.g., determining whether the physics or chemistry was correctly described, or deciding whether the discussions and conclusions make sense), reviewing non-technical aspects of the report (e.g., correct use of grammar, appropriate use of terminologies, logical organization of sections, and whether the report is written clearly for the intended audience), sharing the purpose of the report, and giving suggestions to improve the report.
Reflection/Articulation	2	Mentors had their students explain sections of the report that they thought were unclear. Mentors also questioned/challenged students' claims/conclusions by sharing results from other researchers' work that contradicted students' claims/conclusions.

Note: The "No. of Mentors" column represents the unique number of the interviewed mentors who applied each principle.

tion, and Exploration principles to assist their students. Table 7 describes how the mentors applied these principles during this period.

5.2.6 Period 6: Assisting with writing a final report

The majority of the interviewed mentors ($N = 11$) assisted their students with writing a final report that summarized the students' work during the UR research program. The mentors applied three CA principles: Domain Knowledge, Coaching/Scaffolding and Reflection/Articulation. The principles applied in this period of the UR program are shown in Table 8.

6. Discussion

The interviewed mentors applied many CA principles during the UR program. The CA dimensions applied by the mentors varied among the mentoring periods (see Table 9). For example, when the mentors helped their students write a final report (Period 6), three principles from two CA dimensions were used. On the other hand, when teaching lab skills or experimental techniques to the students (Period 3), 12 principles from all four CA dimensions were applied.

Certain principles dominated each mentoring period. For example, most of the technical content teaching (Period 2 in Table 9) was accomplished by providing various types of references (Domain Knowledge) and discussing them with the students (Coaching/Scaffolding). Of the 12 mentors who discussed teaching technical content to their UR students (Period 2), 11 resorted to strategies categorized in the Domain Knowledge principle, and six used strategies categorized in the Coaching/Scaffolding principle.

In all mentoring periods, the mentors used the Domain Knowledge and Coaching/Scaffolding principles. That is, they provided conceptual, factual, or procedural knowledge and monitored and assisted their students when they performed a task (e.g., reviewing literature, performing experiments, or analyzing results) during every period.

Table 9. Overview of the Cognitive Apprenticeship Principles Applied by the Interviewed Mentors Across Different Periods

CA Dims.	CA Principle	Period 1 $n = 9$	Period 2 $n = 12$	Period 3 $n = 17$	Period 4 $n = 16$	Period 5 n = 8(S), 8(P)	Period 6 $n = 11$
Content	Domain Knowledge	4	11	10	4	1(P)	1
	Heuristic Strategies	4		6		1(P)	
	Control Strategies			1			
	Learning Strategies				1		
Method	Modeling	2		11			
	Explanation			10			
	Coaching/Scaffolding	9	6	14	12	7(S) 8(P)	11
	Reflection/Articulation			2	5	1(P)	2
	Exploration		1	4		5(S) 7(P)	
Sequence	Increasing Complexity						
	Increasing Diversity	1		9			
	Global to Local Skills				4		
Sociology	Situated Learning	1		9			
	Community of Practice		1	9			
	Intrinsic Motivation						
	Cooperation			5	6		

Note: Rows represent CA dimensions and principles and columns represent mentoring periods. The total number of mentors who mentioned a period is indicated by *n*. Mentoring periods are: Period 1 = Teaching a literature review process, Period 2 = Teaching technical content, Period 3 = Training in lab skills or experimental techniques, Period 4 = Assisting with data analysis, Period 5 = Assisting with the creation of presentation slides (S) or a poster (P), and Period 6 = Assisting with writing a final report.

Two principles were not found in the mentoring periods: Increasing Complexity and Intrinsic Motivation. During the interviews, no mentors discussed arranging student activities by increasing complexity (i.e., complexity with respect to the skills or concepts needed) or creating an environment that promoted students' motivation. There was interview data on times when the mentors arranged tasks to help students transfer learned skills from one context to another (e.g., transferring a learned technique from the mentor's work to the student's project), but there was no instance of the mentors' having arranged a series of tasks in order of complexity, that is, beginning with simple tasks and building up to more difficult ones.

There was also no data that showed the mentors creating an environment that helped promote students' motivation. We should note, however, that just because the Intrinsic Motivation principle was not identified from the interviewed mentors, this does not mean that the mentors did not motivate their students. It is possible that various character traits inherent in the mentors, such as caring attitudes and enthusiasm, promoted motivation for their students. To demonstrate application of the Intrinsic Motivation principle, mentors would have needed to design specific activities or environments to motivate their students.

7. Implications

There are two potential implications for this study: (1) Identification of the CA mentoring pedagogies for graduate and postdoctoral researcher mentors and (2) expansion of the CA framework into UR settings.

7.1 Implication 1: Identification of the Cognitive Apprenticeship mentoring pedagogies for graduate or postdoctoral researcher mentors in undergraduate research settings

This study expands the knowledge base of the CA framework. The interviewed mentors applied various CA principles to teach undergraduates knowledge and skills and to support students in the completion of research tasks, in accordance with disciplinary norms.

The author is not aware of any previous studies that use the CA framework to examine the mentoring practices or strategies employed in UR settings. Only a handful of studies have used one or more principles of the CA framework to design and integrate mentoring practices/strategies in such settings as writing courses [28] and peer study groups [29]. Other studies compared students' ability to learn class materials when taught using the CA pedagogies instead of more traditional teaching methods in a civil engineering course [30], a multidisciplinary engineering system design course [31], and multi-year biomedical laboratories [32]. Although these studies attempted to identify and evaluate the critical components of the CA principles across settings and with varied populations, none has examined and identified effective CA mentoring practices used by graduate student or postdoctoral researcher mentors in UR settings.

This is the first empirical study describing the practices of graduate and postdoctoral researcher mentoring that occurred in a UR setting. The study provides specific guidance on how to mentor undergraduates using the CA framework.

7.2 Implication 2: Expansion of the Cognitive Apprenticeship framework into UR settings

This study also shows that the CA framework can be used to provide an accurate representation of mentoring in UR settings and thereby expands the CA framework's application to UR settings and mentoring. As shown in Table 9, graduate and postdoctoral researchers who were mentoring UR students clearly used the CA pedagogies. The interviewed mentors used 14 of the 16 principles from the four CA dimensions during the UR program. The high number of CA principles applied by the mentors confirms that the CA theoretical framework was a suitable choice to elucidate the approaches taken by successful mentors during the UR program. By representing mentors' roles in UR settings through the CA framework, this study has expanded the CA framework's scope from its previously documented uses in a web-based (or multimedia) environment [33–36], K-12 education [37, 38], and higher education courses [28, 30–32]. This study may lay the groundwork for continuing development of the CA framework in the context of both UR mentoring and higher education. Continuous development and refinement of the CA framework will lead to further identification and clarification of effective mentoring practices for UR mentors.

8. Applications

The study results can be applied in a number of ways. One application is to inform current and future mentors of UR students about how experienced and successful UR mentors utilized various CA principles across different mentoring periods. Because the applied CA principles were presented in the context of a UR environment (Table 3 to Table 8), new mentors can replicate mentoring approaches when teaching a literature review process, teaching technical contents, training in laboratory techniques, assisting with data analysis, assisting with the creation of presentation slides or a poster, or assisting with writing a final report and thus potentially have a greater impact on their undergraduate students' research experience.

Furthermore, the findings from this study can support training programs for graduate and postdoctoral researcher mentors. For example, instructors for mentoring training programs can use the principles in Tables 3 to 8 to develop activities or start discussions across different mentoring periods. Specifically, instructors could develop videos for mentoring trainees that show effective mentors training their UR students according to the CA principles identified in Tables 3 to 8. During training sessions, instructors could stop a video periodically to discuss the CA principles being demonstrated by a mentor. Additionally, instructors could have the mentoring trainees form a group and discuss their experiences in training UR students in, for example, operating lab equipment around the CA principles. Such a discussion could unearth additional practical suggestions or actions that the participants could apply. By showing videos and discussing effective mentoring practices in terms of the CA principles, mentoring trainees could learn a number of practical actions to apply when mentoring UR students.

Additionally, instructors could translate the identified CA principles into a checklist that mentoring trainees can review and check off as they mentor their UR students. Instructors could also use the checklist to assess the trainees in UR settings. For example, an instructor could use the checklist to identify what mentors did or did not do during a specific mentoring period. In other words, the checklist could be used as an observation tool to inform and provide feedback to trainee mentors.

9. Limitations and future studies

One limitation of this study is that data was collected only from interviews of nominated graduate and postdoctoral researchers. Although all interviewees mentored one or more UR students and were identified as outstanding mentors by their students, undergraduates' perspectives on what constitute effective mentoring practices are missing from this study. Future studies should ask undergraduates to describe the types of support and guidance that they found helpful to them across identified periods. Additionally, studies examining the similarities and dissimilarities in mentoring practices between nominated and non-nominated mentors will be informative.

Future studies could also examine UR students' development of various research skills after being assisted by mentors who used the CA mentoring practices identified in this study. Specifically, an experiment could be set up in which one group of mentors receives training on CA mentoring practices and the control group does not. Empirical studies examining the effectiveness of these CA mentoring practices in developing UR students' research skills can further justify the need to implement CA mentoring practices when mentoring UR students.

10. Conclusion

This study identified effective mentoring practices in UR settings by interviewing experienced graduate and postdoctoral researcher mentors. The study determined which CA principles the interviewed mentors applied across six distinct UR periods: teaching a literature review process, teaching technical content, training in lab skills or experimental techniques, assisting with data analysis, assisting with the creation of slides or a poster, and assisting with writing a final report. The study findings can inform current and future graduate and postdoctoral researcher mentors about effective mentoring practices in UR settings, and they can be used to develop training programs or materials for these mentors.

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Appendix A: Interview Protocol

1. What types of research activities did you have your student participate in? In other words, what did you ask your student to do during the UR program or in the lab?
   - ☐ For example, did you have your student conduct a literature review, develop hypothesis, build experiments, develop software, collect data, analyze and interpret data, make conclusions, write reports, complete oral presentation, etc.?
2. What knowledge or resources did you provide to help your student complete each research activity? [*Content*]
   - ☐ For example, what knowledge or resources did you provide to help your student conduct a literature review?
3. Did you structure each research activity in a particular sequence for your student? [*Sequence*]
   - ☐ For example, did you give your student particular steps to take/complete while conducting a literature review?
   - ☐ Please explain how you structured each research activity for your student?
4. What did you do to assist your student in gaining required knowledge and developing skills to complete each research activity? [*Method and Sequence*]
   - ☐ Could you walk me through the process you took to teach your student new knowledge?
   - ☐ Could you walk me through the process you took to help your student learn new technical and/or experimental skills?
5. Could you describe the research setting in which you and your student often worked or interacted? For example a description of a lab/classroom/graduate office/field? [*Sociology*]
   - ☐ Did you encourage your student to work in the described research setting? Why or why not?
   - ☐ Were there other UR students, graduate students, researchers, and/or technicians in this place? Did they interact with your student? How did they interact with your student?
     - Did you encourage your student to interact with other graduate students, researchers, or technicians? Why or why not?
     - Do you think having your student situated in the research setting (i.e., location where experiments occurred, location where most interaction occurred) facilitated in the mentoring of your student? Why or why not?
6. Did you meet your student outside the research work setting? If so, where, how often, and what did you do? [*Sociology*]
   - ☐ Did these informal meetings (i.e., outside the research setting) help you build a relationship with your student? How?
7. Did you and your student have (virtual or physical) meetings with faculty/stakeholders/sponsors? What did you do to prepare your student in advance for these meetings?
   - ☐ Did you encourage your student to attend these meetings? Why or why not?

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